TELEMETRY, TRACKING, AND COMMAND CONSOLIDATION IN NASA's DEEP SPACE NETWORK

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ABSTRACT

The Deep Space Mission System at JPL provides tracking, telemetry and command (TT&C) services for a broad spectrum of deep space missions. The TT&C equipment in the Deep Space Network (DSN) is undergoing extensive upgrades and advanced development that will result in more robust systems and standardized customer interfaces for data access and reciprocal support. As part of the upgrade task, known as the Network Simplification Project (NSP), the TT&C architecture and implementation was re-examined. Currently, the TT&C functions are handled in five different subsystems, each with independent controllers whose design does not consider the interaction required between the functions. The NSP project is modernizing the telemetry and command equipment, redesigning the ranging processing and tracking data formats, and consolidating the control of the major elements of the uplink and downlink components.

The new equipment improves reliability and simplifies maintenance by using commercial components, as opposed to the custom built equipment it is replacing. The simplified control architecture consolidates the functions that are interdependent, centralizing the control and reducing the operational unit to a level that does not waste valuable resources. The new ranging architecture enables the ranging and doppler functions to be simply incorporated into the new uplink and downlink equipment and generates a new, expandable tracking data format that avoids the inflexible bit-packed approach in the current products. The new uplink command equipment includes the new CCSDS-standardized Space Link Extension (SLE) service interface, enabling cross-support with other agencies. This paper describes the new architecture, implementation, and lessons learned in the DSN Network Simplification Project.

1.0   INTRODUCTION

The Deep Space Network (DSN) is in the process of upgrading its uplink and downlink equipment for its 34m and 70m antenna subnets. The DSN is part of the Deep Space Mission System (DSMS), which also contains 26m antenna subnets. The upgrade task, known as the Network Simplification Project (NSP), is modernizing many functions and consolidating the control of the major elementso f the uplink and downlink [1], [2]. The current implementation makes use of subsystems designed around limited, specific functions, with each subsystem having its own controller and operator interface. To accomplish a standard activity, an operator might have to configure and control many subsystems. Also, different implementations of a function (e.g., different implementations of telemetry equipment) increase the complexity. Needless to say, this places a burden on the operator and increases the possibility of error.

The consolidation effort of the NSP takes the approach of looking at the different activities performed during standard telemetry, tracking, and command (TT&C) passes and designs the consolidation around these activities. The result is a set of two subsystems (uplink and downlink) instead of the current five. Additionally, custom equipment with reliability issues is being replaced with commercial (or modified commercial) equipment, improving reliability.

The ongoing (it is scheduled to be fully operational by June of 2003) consolidation effort is presented. Three sections are provided. First, we discuss the standard activities that a TT&C pass entails. Next, we briefly provide an overview of the current equipment. The new design is then presented. Finally, some preliminary operational results are given.

2.0   TYPES OF ACTIVITIES

The DSN stations perform all of the standard TT&C functions. Telemetry is obtained by tracking the carrier from the spacecraft, demodulating the subcarrier, synchronizing the symbols, decoding and formatting the data, and sending the formatted frames on to the users. The telemetry function supports multiple types of error correcting codes.

Commanding is performed by receiving the commands from the spacecraft operations team, modulating them onto a subcarrier, then modulating the resulting baseband signal onto a carrier, which is amplified and transmitted from the antenna to the spacecraft. For deep space, commands can be forwarded to the command modulation equipment at the antenna. The user can control the specific first bit radiation time and modulation index.
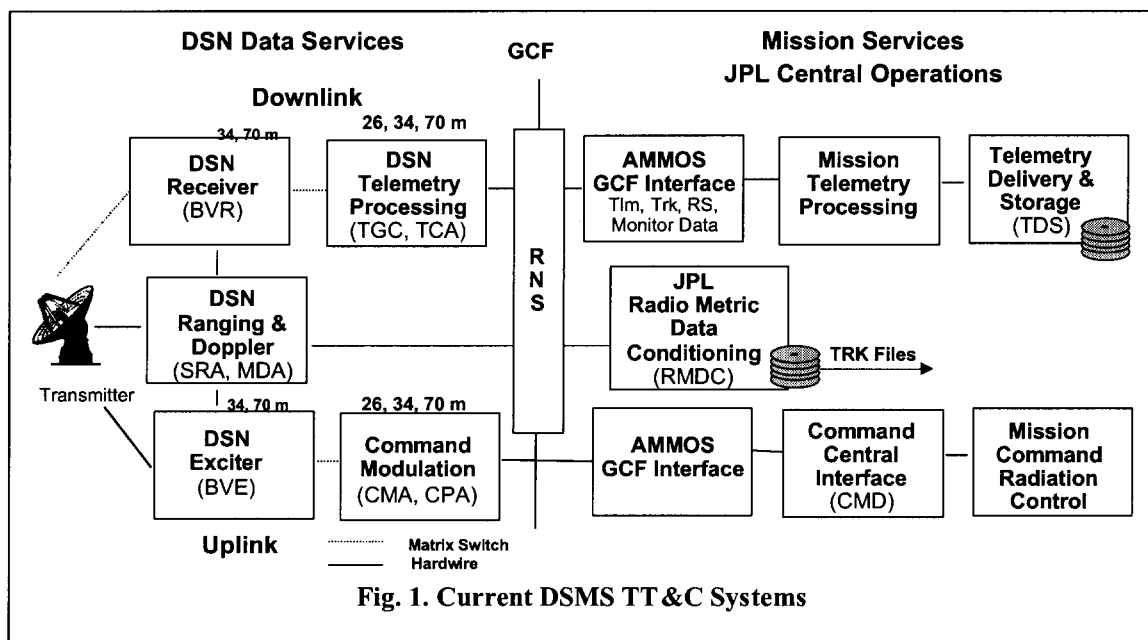
Tracking produces two types of measurements: Carrier Doppler Counts and Range Data. Doppler is a measurement of the change of the carrier phase as a function of time, due to the velocity of the spacecraft. The Doppler measurement is done by very accurately measuring and time-tagging the phase of the uplink and downlink carriers. The ranging data is measured by modulating the uplink carrier with a ranging signal and transmitting it to the spacecraft, which demodulates it and then re-modulates it onto the downlink carrier. On the ground, the signal is demodulated and correlated against the transmitted signal. The alignment that gives the highest correlation provides a measurement of the round-trip light time (RTLT) between the ground antenna and the spacecraft. This is done by differencing the ground transmission and the ground receipt times, modulo the length (in time) of the ranging signal.

The tracking, telemetry, and command functions are not mutually exclusive. For example, Doppler is measured any time there is a downlink signal, and ranging is almost always done when there is downlink telemetry (almost no mission will give up telemetry unless forced to by link margin constraints). Additionally, there is a need to support flexibility. In the near future, there will be multiple spacecraft on Mars that will need to be tracked at the same time, using the same antenna (referred to as Multiple Spacecraft per Antenna, or MSPA). This is accomplished by having multiple sets of downlink equipment and time-sharing the uplink equipment (in other words, the downlinks are continuous, but there can be only one spacecraft receiving an uplink at a time).

3.0   CURRENT TT&C EQUIPMENT

Figure 1 shows an overview of the current complement of DSMS TT&C equipment. Both the DSN equipment and the JPL equipment are shown; in this paper, we are only concerned with the DSN equipment. Currently, there is a combination of relatively new equipment and ten-to-twenty year old equipment, each with its own controller. Specifically, there is equipment to: (a) provide the uplink carrier (the Block V Exciter and the Transmitter, both controlled by the Exciter/Transmitter Controller), (b) control and generate command modulation with a matrix switch to manage hardware redundancy, (c) demodulate the received downlink signal (two Receiver Channel Processors per antenna, controlled by a Receiver Control Computer), (d) decode and process the telemetry (two Telemetry Channel Processors per group, controlled by a Telemetry Group Controller), and (e) generate the Ranging and Doppler data (the Sequential Ranging Assembly, controlled by the Metric Data Assembly).

This design limits the ability for sharing downlink resources among antennas. In the current implementation, the receiver equipment is hardwired to an antenna; thus, each antenna has two sets of receiver processors, whether or not they are needed. The telemetry equipment is switchable, using a patch panel, but only in groups of two channels; again, there is the problem of wasted resources that cannot be simultaneously used at another antenna. The ranging equipment is hardwired to both the uplink equipment and downlink equipment, limiting independent upgrades to each. The uplink system has a matrix switch between the command equipment and the exciter, which does provide the flexibility to share command equipment among antennas. However, this design has added complexity and decreased reliability, with the operations teams continually facing problems and anomalies related to the interaction between the interlinked control components.

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DSN Data Services GCF **Mission Services**
JPL Central Operations

Downlink

34, 70 m   26, 34, 70 m

| DSN Receiver (BVR) | DSN Telemetry Processing (TGC, TCA) | R N S | AMMOS GCF Interface Tlm, Trk, RS, Monitor Data | Mission Telemetry Processing | Telemetry Delivery & Storage (TDS) |

| DSN Ranging & Doppler (SRA, MDA) | | | JPL Radio Metric Data Conditioning (RMDC) | TRK Files |

Transmitter   34, 70 m   26, 34, 70 m

| DSN Exciter (BVE) | Command Modulation (CMA, CPA) | | AMMOS GCF Interface | Command Central Interface (CMD) | Mission Command Radiation Control |

Uplink   ·········· Matrix Switch
———— Hardwire

Fig. 1. Current DSMS TT&C Systems

The equipment was designed around specific, isolated functions (e.g., decoding, command generation, etc.), without consideration of the other functions needed to achieve its objective. Each of the identified equipment above has its own controller, which require operator input to operate. In many cases, configuration for a particular activity must be repeated in multiple assemblies (a good example is that both the receivers and telemetry channels need the predicted symbol rate at which the downlink telemetry data is being sent). This duplication increases both the operator's work and the probability of error. Additionally, as equipment has evolved over the years, the initial purpose of the equipment has been removed while the equipment remains for historical reasons. A good example is the Metric Data Assembly: originally it measured the Doppler frequencies, but now its sole purpose is to format data from the receiver and exciter for transmission back to the projects, with the potential of injecting errors due to configuration mistakes [3].

Another problem is the maintenance of the equipment. Most of the current equipment is custom built and based on 20 year old technology (which was state-of-the-art when it was built). As new antennas have been built, it has been increasing difficult to build new copies, requiring the use of hardware from an increasingly limited pool of spares or the expenditure of money to try to replace obsolete parts.

4.0 NEW DESIGN

The NSP task's mission is to reduce the cost of operations and maintenance by implementing more reliable and operable TT&C systems. In addition to the obvious answer of replacing obsolete equipment and interfaces with modern implementations, the question of how the equipment will be used has also been addressed. Currently, the DSN has five controllers to perform the standard TT&C functions (and this is a reduction in number from what was there in the early 1990's). By looking at how the functions are done (e.g., the linkage between receiver and telemetry processing), it was realized that what were separate subsytems (with separate controllers) could be consolidated into more multi-function subsystems. Specifically, the architecture was divided along the uplink and downlink line, creating two new subsystems: the Uplink Command and Tracking subsystem (referred to as the uplink) and the Downlink Tracking and Telemetry subsystem (downlink).

The scope of the consolidation accomplished by the NSP task can be seen by comparing the existing configuration (Fig. 1) to the new configuration (Fig. 2). The number of controllers and other equipment is significantly reduced. For an uplink, the exciter, transmitter, command modulator, and ranging modulator are all controlled by a single uplink controller; for the downlink, the receiver, telemetry decoding, and ranging correlation are controlled by a single downlink controller. Both controllers provide high level, configuration/prediction file driven control. Normal
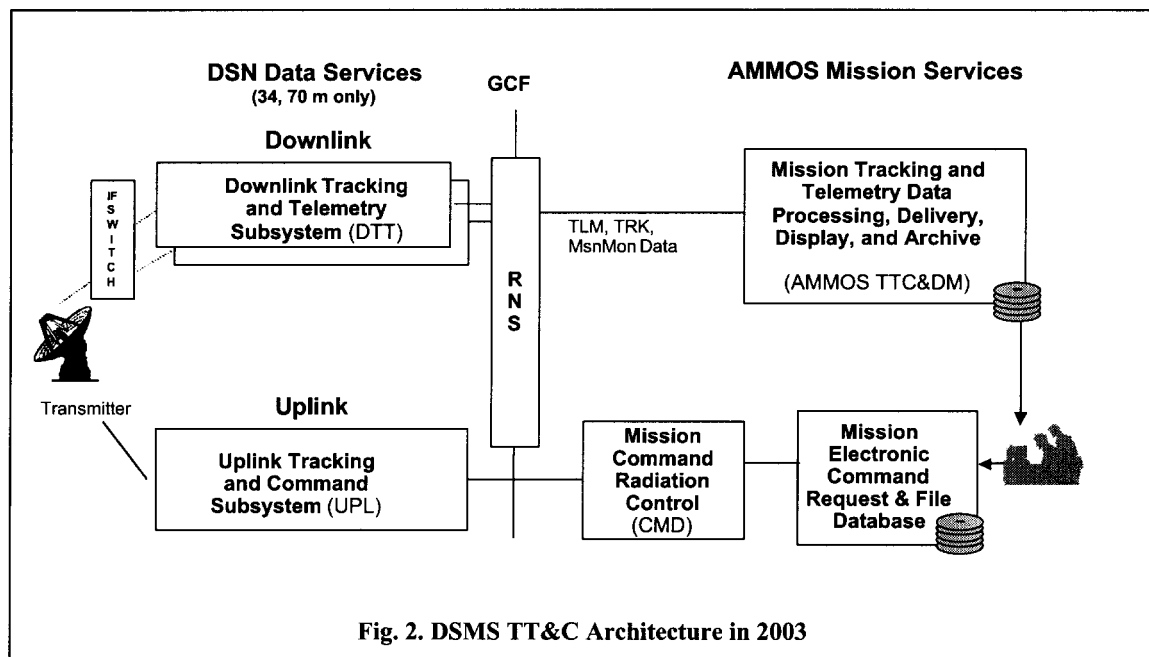
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Fig. 2. DSMS TT&C Architecture in 2003

operations for the entire pass can be done with one or two operator directives. Ranging and Doppler data processing is done at JPL in the new Tracking Data Delivery Subsystem, allowing the removal of the Sequential Ranging and the Metric Data Assemblies which had performed this processing at the station. With the separation of the ranging function into uplink and downlink, the downlink channels (the combination of equipment needed to process one downlink signal) no longer need to be hardwired to a particular antenna. An IF (Intermediate Frequency) switch allows the connection of multiple sets of downlink equipment to one antenna, allowing for MSPA supports, or spacecraft with multiple downlink signals (such as Cassini, which, when doing radio science experiments, will have 1 X-band and 2 Ka-band downlinks simultaneously).

The ranging equipment is currently the only function that ties uplink and downlink together (both in a hardware and system architecture sense). As we mentioned earlier, the current implementation of the ranging equipment relies on custom designed correlator boards, used for both the generation of the ranging signal and the correlation of the transmitted with the received signal. The new implementation makes use of the new capabilities of Texas Instruments (TI) Digital Signal Processor (DSP) integrated circuits. The ranging code generation and correlation can now be done in software running on commercial DSP boards. By separating the code generation and correlation functions into independent assemblies, the splitting of the uplink and downlink ranging functions is possible (both the uplink and downlink equipment will geta ranging processor board), removing the hardware linkage between the two.Al so, since the ranging codes are generated in software, arbitrary codes can be used. The current ranging system can only do sequential ranging codes, but the new system can do both sequential and pseudo-noise (PN) ranging codes, giving greater flexibility and allowing spacecraft regeneration of the ranging signal.

4.1 Uplink

The uplink subsystem contains both new and existing hardware to go along with its new, consolidated controller. Specifically, the existing Block V Exciters and transmitters remain. There is a new Command Modulation Generator (CMG), which replaces the old Command Processor Assembly (CPA) and the Command Matrix Switch Assembly (CMA). In the new architecture, the command equipment is hardwired to the exciters (there are two CMGs per exciter, to provide redundancy), removing the pooling concept that the matrix switch provided (which actually reduced the availability, due to the complexity of the control of the switching). The two hardwired CMGs improve the availability without the added complexity of a central pool of equipment. Also, the uplink ranging equipment is included. Both the uplink ranging equipment and the CMG are based on commercial products, thus removing custom equipment that was costly to maintain.

The new commanding equipment implements the Space Link Extension (SLE) as the interface between itself and the source of the commands to radiate [4]. SLE is the Consultative Committee on Space Data Subsystems (CCSDS) recommendation to provide and promote interagency interoperability. Instead of custom interfaces that change from one agency to another, a common interface is defined, which simplifies the cross-support with other space agencies' control centers and spacecraft. The updated JPL command system uses SLE as the protocol for transmitting the commands from the project. The legacy store-and-forward command protocol is implemented on top of SLE. Additionally, missions operated by the European Space Agency (ESA), such as Rosetta and Integral, and by the Johns Hopkins University Applied Physics Laboratory (APL), such as Contour, use SLE directly.

Another key benefit of the uplink consolidation is improvement in reliability. One of the current problems with the command system (and the main reason for the pooling concept) is that it is impossible to know whether or not the equipment is working until command transmission is attempted. Since the CPA cannot be certain that the exciter's command modulation port is disabled, it cannot take the chance of performing loop back self-tests (it is *highly* undesirable to accidentally modulate commands onto a carrier that is being transmitted). However, with the control of the exciter and commanding now in one controller, the command self-tests can be run safely, since the controller running the self-test can ensure that the modulation port is disabled before starting the test. This self-test capability provides confidence in the hardware without requiring a pool of spares that can be switched in at the last minute.

4.2 Downlink

Like the uplink subsystem, the new downlink subsystem is a combination of old and new equipment. The Block V Receiver (BVR), a digital receiver, is retained. The BVR provides carrier demodulation (residual carrier, suppressed carrier, Quadrature Phase Shift Keyed or QPSK, and Offset-QOSK or OQPSK), subcarrier demodulation, and symbol synchronization. A new Telemetry Processor (TLP) has been developed. The TLP is based on commercial components, providing standard CCSDS telemetry functions (convolutional decoding, Reed-Solomon decoding, differential decoding, frame synchronization, cyclic redundancy code (CRC) check, pseudo derandomization). The CRC and pseudo derandomization are new functions for the DSN. Additionally, the TLP provides expansion capability for the addition of new telemetry functions (e.g., new decoders). Finally, the downlink ranging equipment is integrated into the VME chassis of the BVR.

TheTLP allows for the easy addition two other types of decoders. First is the Block 3 Maximal Likelihood Convolutional Decoder (MCD3). These decoders (which are being phased out) provide decoding of long constraint length convolutional codes (such as the constraint length 15, rate 1/6 code used by Cassini). The other decoder is the new turbo decoder, which runs on the same TI DSPs as does the new ranging implementation. One commercial VME board with eight DSPs will be installed in each TLP to perform symbol domain frame synchronization and turbo decoding, initially up to a rate of 700 kbps [5]; studies are underway to provide the next generation of turbo decoders to support higher decoding rates (such as those proposed for the 2005 Mars Reconnesance Orbiter). Another new feature provided by the TLP is that time-tags are applied to the input symbols (instead of the decoded bits), which improves the accuracy of the time measurement (also, the resolution of the time-tag has been increased to 0.1 μsec).

The integration of receiving, telemetry, and tracking functions provides several improvements to operations. First, acquisition of the downlink signal can be performed for the entire downlink channel a single acquisition operator input, instead of the several operator inputs previously required. Secondly, with the removal of the Metric Data Assembly, the carrier phase measurements are sent directly to JPL, without a middle-man doing formatting and potentially adding errors.

The new subsystem has been designed to provide feedback (both high level and low level) to the operator, assisting him in the operation of the link. First, since the entire downlink now has a single monitor and control point, summary status of the all of the downlink functions can be provided to the operator. High level feedback is also provided by comparing key measurements (frequencies, Signal-to-Noise Ratios (SNRs), etc) with their predicted values, then comparing the difference to a flight project-defined threshold, and reporting to the operator as a "green-red" indicator. The reasoning for the flight project providing the threshold value is the flight project knows how accurate their predictions are and when they want the operator to be concerned. For example, one mission might have enough link margin that a 10 dB SNR variation is not a serious problem, while a mission with a small link

margin would want a tighter constraint. Lower level feedback is provided by retention of actual measurements during the pass, allowing time history plotting.

Another improvement is in the ranging calibration process. Ranging calibrations are required before every pass, to calibrate out the delay of the uplink and downlink subsystems (variations due to day-to-day variation and frequency differences are enough to require calibrations every pass). Currently, the calibrations are very operator intensive and require that the operator keep track of a history to notice anomalous measurements. The new calibration process requires two directives: one for the uplink subsystem and one for the downlink subsystem. The calibration results are monitored and a history for every spacecraft is maintained in software. Each new calibration is compared to the historical results by the controller software. If the measurement is outside of a tolerance, the operator is warned and given the option to accept or reject the measurement (the difference may be valid; for example, the microwave routing of the signals may have been changed, which would change the delay). This calibration value is automatically used in the telemetry time tagging algorithm, which removes the need to do onerous periodic manual calibrations.

The ranging performance will see two improvements from the new implementation. First, in the old hardware, due to the hardware implementation, the first eighth of the clock integration time (which determines the accuracy of the ranging measurement) is used for a course decision and the final seven-eighths are used for the actual measurement. In the new design, the entire clock integration time is used for the measurement. This produces a reduction in the jitter on the measurement for equivalent integration times. Secondly, another fallout of the split in the uplink and downlink ranging is that the computation of DRVID (Differenced Range Versus Integrated Doppler, a measure of the charged particle content of the transmission medium) can now be done with only the downlink carrier phase and downlink range data, without requiring longer range code periods or generating errors when the uplink is ramped [6].

Finally, the downlink channels are connected to the antennas via an IF switch, which allows multiple channels to be connected to a single IF signal. This allows easy configuration for cases such as MSPA (Mars operations) or multiple downlink carriers from a single spacecraft (e.g., Cassini). With the old equipment, one controller controlled two channels that are independent. This is error prone – a command meant for only one channel can easily be sent to both. The new configuration, with one controller per channel, prevents one operator entry from going to multiple channels.

5.0   PRELIMINARY RESULTS

Testing with spacecraft (mainly Cassini) started in the first half of 2002. The main emphasis has been on ranging data, since the ranging system is a completely new implementation. Ranging data from two-way passes using the NSP equipment was used along with the standard legacy passes prior to and after the test passes. Figure 3 [7] shows that the Range results align with the legacy data, providing an initial validation of the new implementation (the NSP results are circled). Testing with multiple spacecraft will continue through the rest of 2002, leading up to the first installation, which will go operational at the end of December, 2002.

6.0   CONCLUSION

The new consolidated uplink and downlink architecture of the DSN has been presented. This implementation reduces the number of control points that an operator must deal with from five to two, improves coordination between low-level functions, and increases operator visibility of the TT&C functions. The new subsystems will be operational at DSN 70m and 34m antennas by June, 2003.

7.0   REFERENCES

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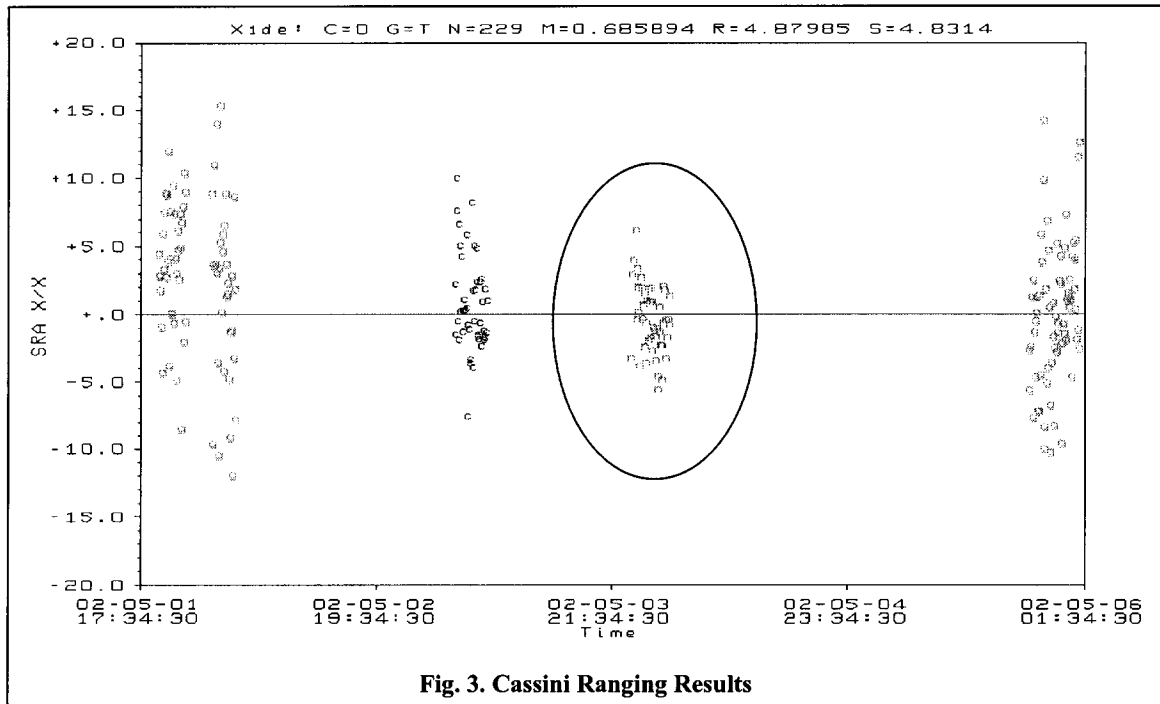
Fig. 3. Cassini Ranging Results

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8.0 ACKNOWLEDGEMENTS

9.0 BIOGRAPHY

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